Army Research Laboratory

Imaging With Magnification Test Procedure

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ARL-TN-0333 September 2008

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Adelphi, MD 20783-1197

ARL-TN-0333 **September 2008**

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
September 2008	Final	

4. TITLE AND SUBTITLE
Imaging With Magnification Test Procedure

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Michael J. Ferry, William Shensky III, Andrew G. Mott

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Sensors and Electron Devices Directorate
AMSRD-ARL-SE-EM
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TN-0333

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Although modern cameras have advanced to the point where pixel size approaches 4 microns, we have yet to achieve the submicron size necessary to accurately resolve focused laser beams. Present methods such as pinhole scans and knife edge scans assume spatial wave forms to fit the transmission, and those assumptions may be erroneous. This technical note details a method of imaging with calibrated magnification and commercial laser beam profiling software to accurately measure beam sizes. Experimental layout is detailed, all reference material included, and the equations stated.

15. SUBJECT TERMS
Imaging, laser beam, magnification, USAF 1951

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR	18	Michael Ferry
					19b. TELEPHONE NUMBER (*Include area code*) (301) 394-0938

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.

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1. Introduction

This technical note details a procedure for accurately measuring the laser beam diameter of a focused laser beam when the spot size is on the order of or less than the camera pixel dimension of a commercial beam profiling system. Imaging with magnification is used to expand the beam to a large enough size to have many pixels across the beam. Magnification is calibrated with test patterns, and the actual beam size is determined. This technical note is intended for the bench level scientist.

2. Theory of Magnification

The relevant equations (*1*) are

$$1/f_{im} = 1/S_o + 1/S_i \tag{1}$$

$$M = - S_i / S_o \tag{2}$$

where,

f_{im} = focal length of the imaging lens

S_o = object distance, the distance from lens to the Air Force test pattern

S_i = image distance, the distance from lens to the camera

M = magnification

Solving equations 1 and 2 for S_i gives

$$S_i = f_{im} \times (1–M), \tag{3}$$

which is the image distance as a function of the magnification and focal length. Solving equation 1 for the corresponding object distance gives,

$$S_o = 1/(1/f_{im}–1/S_i). \tag{4}$$

Negative magnification means an inverted image, which is what occurs with single lens imaging. Equation 3 makes apparent that image distance increases as a product of imaging lens focal length and magnification. When imaging with magnification, the negative lens with the shortest focal length available should be used to reduce the amount of bench space needed for measurement. For magnification, $|S_i| > |S_o|$, the image distance is the limiting factor.

A typical top-hat beam focuses to

$$d_{focus} = 2.44 \times \lambda \times f_{sys} / d_{lens} \quad \text{(top-hat beams)} \tag{5}$$

where d_{focus} = the diameter of the Airy disk in the focal plane; λ is the wavelength; f_{sys} is the focal length of the lens of the system lens; and d_{lens} is the near field diameter of the laser beam at that lens.

To determine how much magnification is required, assume a resolution requirement that the magnified beam is spread across at least 10 pixels on the CCD (*2*).

$$d_{mag} > 10 \times p \tag{6}$$

where d_{mag} is the beam diameter of the magnified beam on the camera, and p is the smallest pixel dimension. The magnified diameter of the laser beam on the camera is equal to the magnification times the real beam diameter at the focus of the system lens,

$$d_{mag} = M \times d_{focus} \quad \text{or} \quad M = d_{mag} / d_{focus.} \tag{7}$$

Solving equations 7, 6, and 5 for magnification gives

$$M > 10 \times p / d_{focus.} \tag{8}$$

Note: if plane waves are used instead of Gaussian beams, equation 5 becomes

$$d_{focus} = (4/\pi) \times \lambda \times f_{sys} / d_{lens} \quad \text{(Gaussian beams).} \tag{9}$$

Real beams are not diffraction limited, so the minimum required magnification predicted by equation 8 may be excessive.

3. Test Procedure

The first part of the procedure is to block out the experiment for desired magnification and image the test pattern on the camera. To begin, obtain a rough estimate of object and image distances. Use the equations from the theory of magnification section to determine the object and image distances needed for the imaging lens. This will help block out the lens and camera positions on the optical bench. See figure 1.

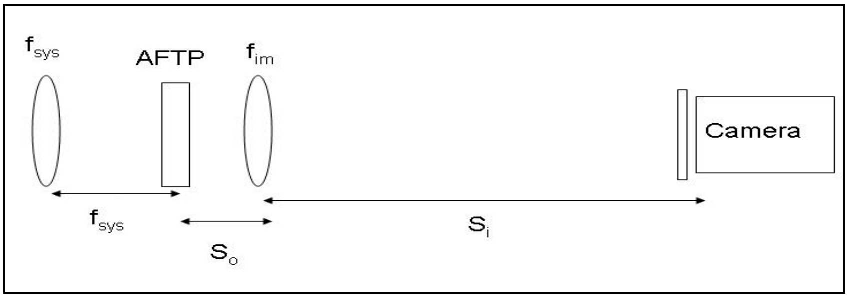

Figure 1. Layout of imaging with magnification experiment.

NOTE: The system lensF_{sys} focuses the laser beam near the location of the Air Force Test Pattern (AFTP). The imaging lens f_{im} is located at the object distance S_o from the test pattern. The camera is located at the imaging distance S*i* from the imaging lens.

Once the system is blocked out according to distances predicted by theory, it is then time to image the test pattern. To do this, begin by observing on the bench where the system lens focuses the laser beam. Mark the focal position and block or shutter the laser beam. Remove the system lens, f_{sys}, and place an Air Force Test Pattern (AFTP) at the marked position.

Illuminate the transparent AFTP with a fiber light. The fiber light is desirable since bright light is required to image the test pattern. Gray scale rather than color scale is used on the camera to get fine resolution of bar edges. It is helpful to have the test pattern on an X-Y stage to easily scan the pattern across the beam for the series/element that fills the camera array. Place the imaging and system lenses on a Z-axis translation stages. Adjust the object distance with the imaging lens micrometer until a sharp, focused image of a single 3 bar element fills the camera array.

Sometimes it is difficult determining from the camera image which group and element is imaged on the camera. Translating the pattern with the X-Y micrometer to search for the group/element numbers, is one way to decide which element was imaged. Another quick way is by placing an 8.5 by 11 in. white paper in front of the camera to display a large section of the magnified image of the test pattern. All the other series/elements that image outside of the active area of the camera can then be seen.

Spatial distances separating the bars on an AFTP are well known and can be acquired by referring to the appropriate table for an AFTP. Figure 2 shows what a typical AFTP looks like (*3*).

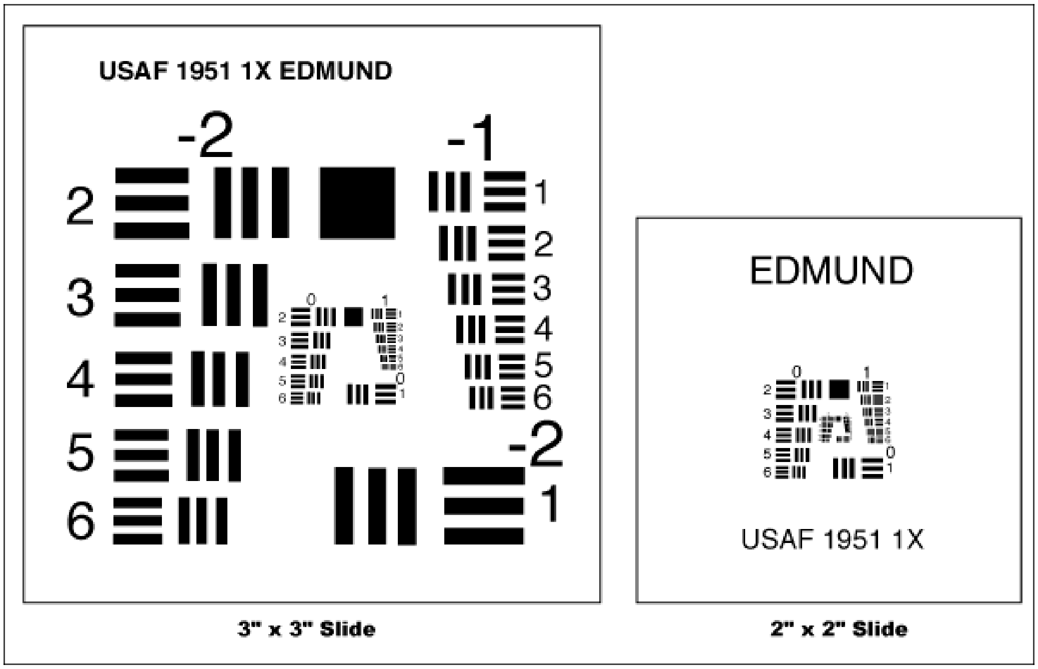

Figure 2. Typical test patterns.

NOTE: Shown are commercially available examples of the standard USAF 1951 test pattern. Group number is the large number on top of the largest element of the group, and element number is either to the left or right of the pattern element.

The group number (large number above the first one in the series) and an element number (smaller number to the left of the series, ranging from 1 to 6) uniquely identify any 3 bar element. In general, the elements descend in group number in a clockwise inward spiral. The exception is the first element of the left most series appears in the lower right hand corner of the test pattern.

The relative dimensions on any given element (*4*) are found in figure 3.

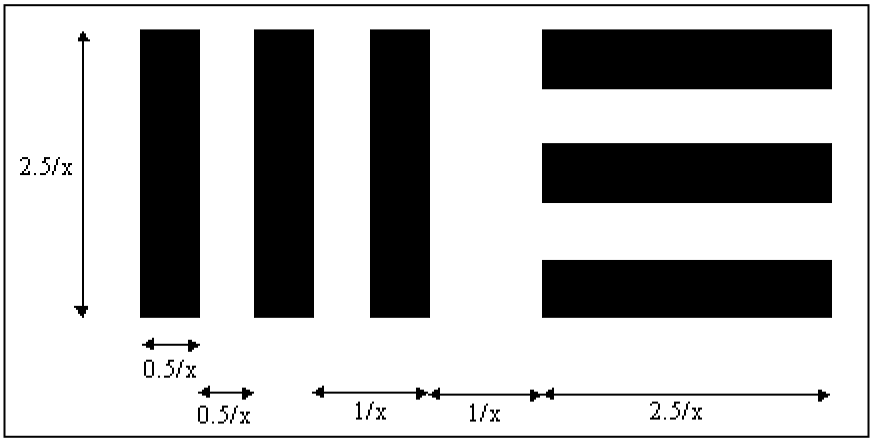

Figure 3. Relative dimensions of a test pattern element.

NOTE: The quantity x is a spatial frequency of line pairs per millimeter (units mm^{-1}) and 0.5/x is the width of a single bar (mm), with 2.5/x being the length of a bar.

Here x is the lines per millimeter, which may be obtained for any given group/element from a lookup table. The lookup table is found in table 1. Notice that standard 2 in. square commercial test patterns typically begin with group 0 and leave off groups –1 and –2.

Table 1. Lookup table for spatial frequencies of the USAF test pattern.

Number of Line Pairs / mm in USAF Resolving Power Test Target 1951											
Group Number										**For High Res only**	
Element	-2	-1	0	1	2	3	4	5	6	7	8	9
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0	256.0	512.0
2	0.280	0.561	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144.0	287.0	575.0
3	0.315	0.630	1.26	2.52	5.04	10.10	20.16	40.3	80.6	161.0	323.0	645.0
4	0.353	0.707	1.41	2.83	5.66	11.30	22.62	45.3	90.5	181.0	362.0	-----
5	0.397	0.793	1.59	3.17	6.35	12.70	25.39	50.8	102.0	203.0	406.0	-----
6	0.445	0.891	1.78	3.56	7.13	14.30	28.50	57.0	114.0	228.0	456.0	-----

NOTE: Each number in this table is x/2, half a line pair per millimeter. Invert numbers from this table to get the width of a single bar.

Alternatively, the spatial frequency for a group/element may be calculated by

$$x = 2^{(g + 1 + (e-1)/6)} \qquad (10)$$

where g = group number, e = element number, and x is the line pairs per mm.

After the group and series numbers of the imaged element are known, the next step is to measure the size of the image on the camera. Typical commercial laser beam profilers permit the user to

manually slew a cursor across the image, and record the cursor position. To avoid noise issues with imaging, measure 2 line pairs to average out flaws in image position.

For example, assume the 3 vertical bar element is imaged on the camera (see figure 4). Most beam profilers have a cross section feature. In this case, position the cursor and observe the horizontal cross section where it is a simple matter to go between identical points on the square wave form (shown in red along bottom of figure 4). To measure the image size in x, move the cursor to the left edge of the first vertical bar element, record the horizontal location, then move the cursor horizontally to the left edge of the 3rd element and record the location. The difference in these two positions divided by 2 is the magnified width of a line pair: 1/x. Looking up x from table 1, the magnification, M, may be then calculated from equation 7 by letting the magnified width of a line pair equal d_{mag} and the actual width of the line pair from the lookup table be d_{focus}.

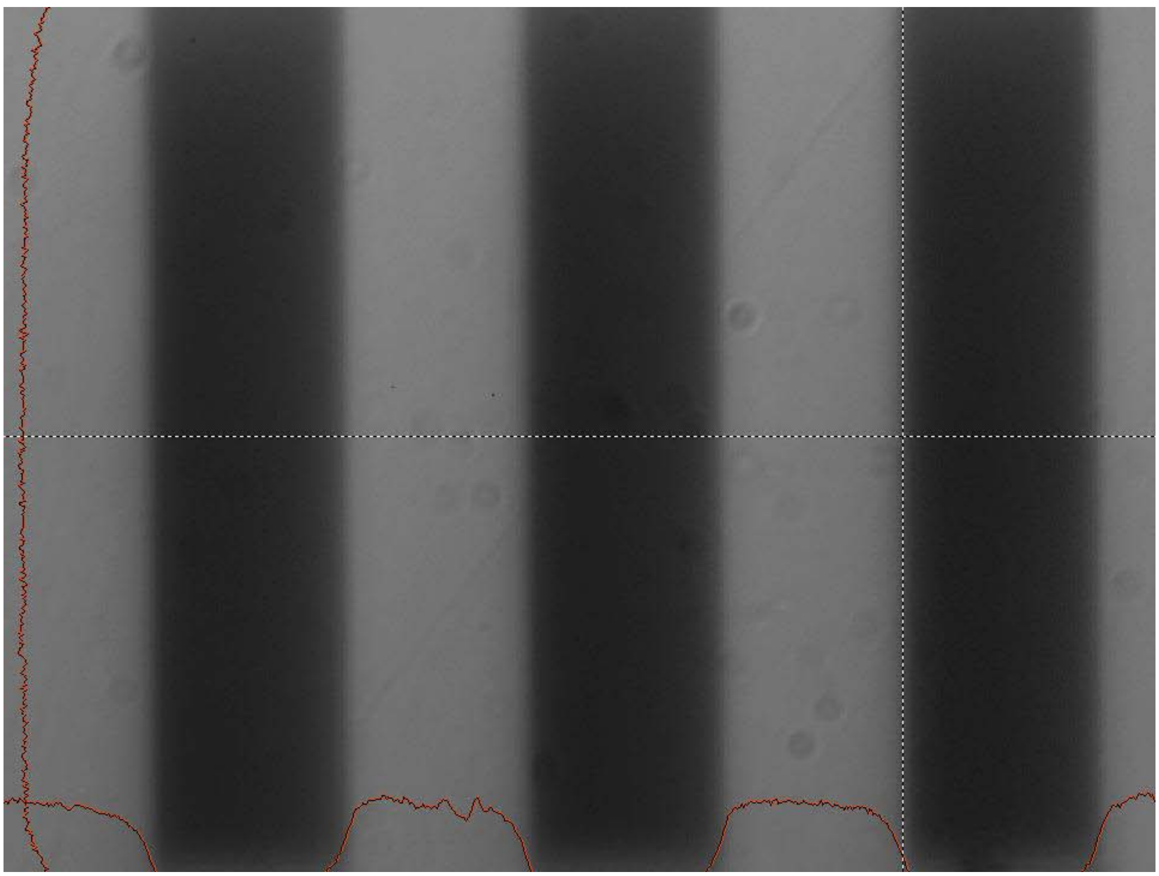

Figure 4. Example image of a magnified element.

NOTE: Shown is group 2, element 5 as captured by a COHU 6612 digital camera. The cursor presently is at position (4861, 2416 μm) at the left edge of bar 3, and the left edge of bar 1 was at (1020, 2416 μm). Two periods of this element are 315 μm, and the magnified distance for two periods was 4861–1020 = 3841 μm, implying a 12.2 × magnification.

The next part of the procedure involves putting the system lens focus at the AFTP position. Return the system lens, f_{sys}, and remove the test pattern. During this part, *do not move the*

imaging lens or camera. Moving either the imaging lens or camera changes the magnification and forces recalibration of magnification. Put filters in front of the system lens to reduce the laser intensity to a very low level that will not damage the camera or unshutter the laser. Make slight adjustments to the system lens position with the translation stage to put the focus where the AFTP used to be. The system lens is in the correct position when the beam size on camera is at a minimum.

The final part of the procedure is to measure the magnified image size on the camera. With the system lens position optimized, use the beam profiling software of the camera to determine the magnified image diameter on the camera, and then divide that by M to get the actual image size. Beam profiles may be properly scaled by dividing by the magnification.

The procedure outlined above calibrates magnification first, and then measures the spot size. Sometimes it is advantageous to do the reverse, where the spot size is measured and then the experiment disassembled to measure magnification. In this “calibrate last” variant, it is important to place the AFTP exactly at the focus of the system lens, and rather than translate the system lens in z, the AFTP is translated in z to bring it into focus on the camera. Just as in the “calibrate first” method, the calibrate last procedure requires the image distance to remain constant after the magnified laser beam has been measured, and the imaging lens and camera should not be moved to avoid having to re-measure the magnified beam diameter.

The steps for the calibrate last procedure are (1) with the laser on, adjust the imaging lens position to minimize spot size on the camera and record the magnified diameter, (2) block the laser and pull the system lens, (3) insert the AFTP on a 3 axis stage, adjusting x - y to get the appropriate element on the array then z to focus that element on the array, and (4) determine the magnification by measuring 2 periods of the 3 bar pattern in a manner similar to that described for the calibrate first procedure. The calibrate last procedure is most useful when it is desirable to hold the system lens position fixed. Calibrating first permits multiple system lenses to be used and resulting focal diameters measured with a single calibration.

Finally, it is worth noting the methods developed for imaging with magnification (i.e., expanding very small laser beams onto cameras), may also be used for the inverse case of imaging with demagnification, where the size of a very large laser beam needs reducing to fit on a small camera array. The main differences in imaging with demagnification are (1) the object distance is now much smaller than the image distance, and (2) the large beam may be rough measured and compared to the known array size to estimate the required demagnification.

4. Numerical Example

A two-times diffraction-limited 532 nm top-hat laser beam, with a d_{lens} = 60 mm, is focused by an f_{sys}=100 mm lens. From equation 5, the predicted diffraction limited diameter is

$$d_{focus} = 2.44 \times (0.532\ \mu m) \times (100\ mm)/(60\ mm) \sim 2.2\ \mu m.$$

Since the beam is two-times diffraction limited, the real diameter should be approximately 4 µm at focus. Assume the camera available to measure this beam has a p = 5µm pixel dimension. From equation 8, the desired magnification is:

$$M > 10 \times (5\ \mu m)/(4\ \mu m) = 12.5.$$

With an f_{im} = 25.4 mm imaging lens, equation 3 can be used to determine the image distance,

$$S_i = (25.4\ mm) \times (1\text{–}12.5) = 292\ mm \sim 11.5\ in.$$

where distances have been converted to inches because lab benches are ruled in inches and the point of this calculation is to estimate layout spacing. From equation 4, the corresponding object distance is:

$$S_o = 1/(1/(25.4\ mm) - 1/(292\ mm)) = 23.4\ mm \sim 1\ in.$$

If the available bench space is 30 in., and the camera takes up 4 in of that, 26 in. is left for the object and image distances, which is more than the required ~12.5 in. The camera is placed S_o = 24 in. from the imaging lens and the AFTP is mounted on a translation stage just under 1 in. from the imaging lens.

Assume the camera has a 4 by 4 mm active area. To accurately measure the laser beam, the largest magnified beam used on this camera should be ~3 mm, or 75% of the active area. In principle, it could go as high as M = 3 mm/0.004 mm = 750, but bench space limits the magnification to a much lower number ~24/1 or M = 24. The beam diameter should be about d_{mag} = 4 × 24 = 96 µm on the camera, and have ~96/5 = 19 pixels across the beam.

To get a single 3 bar element to fill up 75% of the active area, the bar length, when magnified, should be 3 mm. For a magnification of 24, the actual bar length should be 3 mm/24 = 125 µm. From figure 3, the bar length is related to the spatial frequency by

$$2.5/x = 125\ \mu m \Rightarrow x = 2.5/0.125\ mm = 20 \text{ line pairs per mm.}$$

The chart in table 1 shows that group 3, element 3 has x/2 = 10.1 = > x ~20 line pairs per mm. Therefore, group 3, element 3 should be roughly the correct element that fills up the 4 by 4 mm array.

Typical beam profiling software yields the most accurate results when data > 2.5 times the beam diameter is excluded from the calculation. Therefore, a 96 μm diameter beam should have a calculation exclusion diameter of 240 μm. On some profiling systems it is possible to define an exclusion diameter, while on others exclusion is achieved by digitally zooming in the profiling software to push extraneous data outside the calculation region. In the latter method to achieve an exclusion diameter filling 75% of the screen, then the 3 mm/0.24 mm = 12.5 × camera zoom would be required.

5. Summary

A procedure has been detailed for the quantitative measurement of small laser beams by the method of imaging with magnification. Equations were supplied to estimate approximate distances for the layout of the actual experiment. Usage of USAF 1951 to quantify magnification was detailed. A numerical example was provided to underscore the method.

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